https://doi.org/10.17221/390/2025-PSE

Remediation of cadmium-polluted acidic soil with dolomite and calcite to enhance soil health and pak choi growth

*Muhammad Shaaban[1]**, *Lei Wu[2]*, *Aneela Younas[1]*, *Yupeng Wu[3]**

[1]*College of Agriculture, Henan University of Science and Technology, Luoyang, P.R. China*
[2]*Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing, P.R. China*
[3]*College of Resources and Environment, Huazhong Agricultural University, Wuhan, P.R. China*
**Corresponding authors: shabanbzu@hotmail.com; wyp19851205@mail.hzau.edu.cn*

Citation: Shaaban M., Wu L., Younas A., Wu Y.P. (2025): Remediation of cadmium-polluted acidic soil with dolomite and calcite to enhance soil health and pak choi growth. Plant Soil Environ., 71: 873–882.

Abstract: Cadmium (Cd) contamination in agricultural soils threatens crop productivity and food safety. This study examined the use of dolomite and calcite amendments in reducing Cd toxicity in pak choi grown in Cd-contaminated soil. Treatments included: control (CK), Calcite 1 (Cal1, 10 g/kg soil), Calcite 2 (Cal2, 20 g/kg soil), Dolomite 1 (Dol1, 10 g/kg soil), and Dolomite 2 (Dol2, 20 g/kg soil). Amendments significantly increased soil pH ($P \leq 0.05$), with Cal2 (6.5) and Dol2 (6.2) achieving the highest values at harvest. Cd availability declined ($P \leq 0.05$), with Dol2 being the most effective, reducing the toxicity characteristic leaching procedure-extractable Cd from 0.03 to 0.01 mg/kg, NH_4NO_3-extractable Cd from 0.05 to 0.02 mg/kg, and $CaCl_2$-extractable Cd from 0.40 to 0.01 mg/kg. Dol2 improved biomass and chlorophyll content, while reducing Cd accumulation in shoots by 73.3% and in roots by 70% relative to the control. Antioxidant enzymes were regulated, with decreased peroxidase and superoxide dismutase indicating reduced oxidative stress, while Dol2 maximised urease, catalase, invertase, phosphatase, and phenol oxidase activities. Dissolved organic carbon and microbial biomass carbon also increased, thereby enhancing microbial activity. Dolomite and calcite significantly reduced biological concentration factors, biological accumulation coefficients, and translocation factors, thereby restricting Cd uptake. Overall, dolomite, especially at higher levels, effectively mitigated Cd toxicity, improved plant resilience, and enhanced soil health in contaminated systems.

Keywords: soil remediation; soil pH amendment; phytoavailability; plant oxidative stress; soil enzymatic activity

The cadmium (Cd) contamination in agricultural soils poses devastating effects on soil health, plant growth, and food safety (Zhou et al. 2024). Once introduced into the soil, Cd remains persistent and is readily bioavailable in acidic soils, posing a severe risk to plant uptake and, subsequently, human health (Papadimou et al. 2024). Acidic soils exacerbate the mobility and bioavailability of Cd, thereby increasing its toxic effects on plants (Cui et al. 2024). Leafy vegetables such as pak choi (*Brassica rapa* subsp. *chinensis*) are prone to Cd accumulation (Li et al. 2024). Various soil amendments have been explored to mitigate Cd contamination, with lime-based materials being among the most effective options (Bashir et al. 2020, Li et al. 2023a). Dolomite ($CaMg(CO_3)_2$) and calcite ($CaCO_3$) are two widely used carbonate minerals that serve as soil amendments to neutralise soil acidity and immobilise heavy metals (Zhang and Liu 2022). Dolomite and calcite can contribute to Cd immobilisation through cation exchange processes, and the formation of insoluble Cd-carbonate complexes (Vrînceanu et al. 2019, Zhang and Liu 2022). Increasing pH promotes the formation of $CdCO_3$, contributing to the immobilisation of Cd in con-

Supported by the Fundamental Research Funds for Henan University of Science and Technology, Project No. 4024-13510002.

https://doi.org/10.17221/390/2025-PSE

taminated soils (Li et al. 2023a). Enhanced microbial activity under improved pH conditions may facilitate Cd immobilisation through mechanisms such as biosorption, bioaccumulation (Xu et al. 2022). Soil enzymes, which are sensitive indicators of soil health, can be inhibited by Cd contamination but may recover upon the application of amendments, contributing to nutrient cycling and overall soil functioning (Xu et al. 2022, Cui et al. 2024). Therefore, the combined physicochemical and biological responses of the soil system should be considered when evaluating the effectiveness of amendments.

Pak choi is one of the most widely consumed leafy vegetables in Asia and is known to accumulate Cd in its edible tissues readily. This characteristic makes pak choi a sentinel species for assessing Cd contamination risks to human health through dietary intake (Park et al. 2025). At the same time, its fast growth rate, high biomass production, and tolerance to moderate Cd stress make it a useful model for studying Cd uptake and translocation mechanisms, with potential implications for phytoremediation of contaminated soils (Li et al. 2024). Therefore, investigating Cd dynamics in pak choi not only contributes to food safety management but also supports the development of sustainable remediation strategies for Cd-polluted farmlands.

We hypothesised that the application of dolomite and calcite would significantly reduce Cd bioavailability in acidic soils by increasing soil pH and facilitating Cd immobilisation. Increased microbial and enzymatic activity associated with amendment application will further enhance soil health and contribute to Cd stabilisation, leading to improved pak choi growth. The primary aim of the present study was to assess the effectiveness of dolomite and calcite in remediating Cd-polluted acidic soil and enhancing soil health to support the growth of pak choi.

MATERIAL AND METHODS

Experimental setup and treatments. Acidic soil was collected from Xian-Ning city, Hubei, China. The soil had a pH of 5.2, an organic carbon content of 1.16%, and a cation exchange capacity of 151 $mmol_+$/kg. Cadmium was not detected in the soil samples tested. The soil texture was classified as silty clay loam (clay: 30.64%, silt: 56.93%, sand: 12.43%; USDA Soil Texture Classification). Soil is classified as Ultisols (kaolinitic thermic typic plinthudults) (Soil Survey Staff 2010). The dissolved organic carbon content was 52 mg/kg, while the microbial biomass carbon content was 90 mg/kg. The available N, P, K, and Mg levels were 85, 22, 36, and 16 mg/kg, respectively. To simulate Cd contamination, 5 mg/kg Cd was added to the soil in the form of cadmium chloride ($CdCl_2$). The contaminated soil was incubated for 30 days at 25 °C to acclimate and stabilise Cd before the application of soil amendments. Then, five treatments were applied to the soil, with each treatment replicated three times:

Control (CK): no amendments applied.
Calcite 1 (Cal1): 10 g/kg of soil.
Calcite 2 (Cal2): 20 g/kg of soil.
Dolomite 1 (Dol1): 10 g/kg of soil.
Dolomite 2 (Dol2): 20 g/kg of soil.

The calcite and dolomite used in this study were obtained from a commercial supplier (ShiJiaZhuang, China). Both materials were finely ground and sieved to a particle size of < 0.13 mm before use. The chemical purity of calcite and dolomite was 99.2% and 98.5%, respectively. Dolomite contained 12.78% Mg and 21.66% Ca, corresponding to an approximate Mg/Ca molar ratio of 0.70, while calcite contained 39.62% Ca with trace Mg (< 0.5%). X-ray diffraction (XRD) analysis confirmed that the dominant minerals were dolomite [$CaMg(CO_3)_2$] and calcite ($CaCO_3$). After the application of amendments, the treated soils were incubated for an additional 15 days to allow for stabilisation and equilibration of soil conditions. Subsequently, 7-day-old pak choi seedlings were transplanted into pots having 4 kg of treated soil per pot. The pak choi seedlings were grown under controlled conditions at 28 °C, 70% relative humidity, and a photoperiod of 16 h of light per day. Water was supplied every three days to maintain soil moisture. The plants were cultivated for a total of 45 days before harvest.

Plant analysis. Fresh and dry weights of roots and shoots were recorded. Drying was performed at 65 °C for 48 h, followed by 105 °C for 24 h. Chlorophyll contents (*a* and *b*) were examined according to the Chtouki et al. (2021) by the measurement of the chlorophyll content index (CCI) using a Chlorophyll meter (C.L.-01Hansatech Instruments Ltd., King's Lynn, Norfolk, UK). Cd concentrations in roots and shoots were measured after digestion with a three-acid (HCl-HNO_3-$HClO_4$) mixture and analysed using an atomic absorption spectrophotometer (AAS-240FS, Agilent Technologies, Santa Clara, USA) as described by Chen et al. (2023). Hydrogen peroxide (H_2O_2) and malondialdehyde (MDA) contents were quantified using the thiobarbituric acid method, as described by

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Zha et al. (2022) and Kamran et al. (2019). The activities of antioxidant enzymes, including catalase (CAT) by the ultraviolet absorption method, glutathione (GSH) by the 1 mmol/L dinitrothiocyanobenzene method, peroxidase (POD) by the guaiacol method, and superoxide dismutase (SOD) by the nitrogen blue tetrazolium method, were assessed according to Kamran et al. (2019). Biological coefficient factor (BCF), biological accumulation coefficient (BAC), and translocation factor (TF) were calculated using the following equations as described by Malik et al. (2010):

$$BFC = \frac{\text{Cd in root}}{\text{Cd in soil}} \quad (1)$$

$$BAC = \frac{\text{Cd in shoot}}{\text{Cd in soil}} \quad (2)$$

$$TF = \frac{\text{Cd in shoot}}{\text{Cd in root}} \quad (3)$$

Soil analysis. The soil pH was measured using a pH meter in a 1:2.5 dilution ratio (soil:distilled water). The activities of key soil enzymes, including urease, catalase, invertase, phosphatase, and phenol oxidase, were determined (Shaaban et al. 2023a). Available N was determined as the sum of NH_4^+-N and NO_3^--N, extracted using 1 mol/L KCl solution and quantified by continuous flow analysis (Shaaban et al. 2023b). Available P was measured using the Olsen P method after extraction from soil and analysed on a UV spectrophotometer (Ullah et al. 2016). Available K was determined by extracting with 1 mol/L CH_3COONH_4 (pH 7.0) and examined using a flame photometer (Yuan et al. 2021). Additionally, soil dissolved organic carbon (DOC) and dissolved organic nitrogen (DON), as well as microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN), were analysed using an extraction method with an elemental analyser (C/N elemental analyser, VarioMax, Langenselbold, Germany) according to Shaaban et al. (2023a). Cd content in soil was examined after soil digestion with a three-acid (HCl-HNO_3-$HClO_4$) mixture and analysed using an atomic absorption spectrophotometer (AAS-240FS, Santa Clara, USA). Cd was assessed in the soil as TCLP-extractable Cd, $CaCl_2$-extractable Cd, and NH_4NO_3-extractable Cd (Bashir et al. 2018). TCLP was used with an acetic acid/sodium acetate solution (pH ~4.93). This method assesses the potential mobility of Cd under conditions of acid leaching, providing an estimate of environmental risk and the potential for Cd leaching. The $CaCl_2$ extraction (0.01 mol/L $CaCl_2$) was selected because it represents the exchangeable fraction of Cd, which is weakly bound to soil particles and easily displaced by cations in the soil solution. This fraction is considered readily plant-available and responsive to soil management practices, particularly those related to pH and ionic strength. The NH_4NO_3 extraction (1 mol/L NH_4NO_3) was included as it targets the more weakly sorbed and solution-phase Cd, encompassing both the free Cd ions and those loosely associated with exchange sites. This extractant represents an even more mobile and bioavailable fraction than $CaCl_2$, as NH_4^+ has a stronger competitive displacement effect compared to Ca^{2+} ions (Bashir et al. 2018).

Statistical analysis. The means of treatments (three replicates) and standard errors were calculated using MS Excel (Washington, USA). Statistical analyses were accomplished using one-way analysis of variance (ANOVA) in SPSS version 16 (SPSS Inc., Chicago, USA) to assess the effects of treatments. Post-hoc comparisons were conducted using Tukey's *HSD* (honestly significant difference) test, and significance was determined at $P \leq 0.05$.

RESULTS

Soil pH and Cd contents. Calcite was more effective ($P \leq 0.05$) than dolomite in increasing soil pH, with the highest pH level (6.5) recorded in the Cal2 treatment at the time of pak choi harvest, while the pH in the Dol2 treatment reached 6.2 (Figure 1A). The total Cd concentration in soil showed no significant difference among treatments, ranging from 4.80 mg/kg in the control to 4.93 mg/kg in the Dol2 treatment (Table 1). However, both amendments significantly ($P \leq 0.05$) reduced the extractable Cd fractions (TCLP-, $NH_4NO_3^-$, and $CaCl_2$-extractable Cd), suggesting that immobilisation rather than removal was the dominant mechanism of Cd stabilisation. The maximum soil Cd content was recorded in the Dol2 treatment, and thus, TCLP-extractable Cd, NH_4NO_3-extractable Cd, and $CaCl_2$-extractable Cd were 0.01, 0.02, and 0.01 mg/kg, respectively. In contrast, these values were 0.02, 0.05, and 0.04 mg/kg in the CK treatment (Figures 1B–D).

Soil enzymes. Soil enzyme activities were compared with those of the Cd-contaminated control (CK) without any amendments, which served as the baseline for assessing the effects of the amendments. Soil enzyme activities were adversely affected ($P \leq 0.05$) by Cd contamination, and the application of calcite and dolomite enhanced the activities of all measured enzymes. Notably, the Dol2 treatment had the most pronounced impact on enzyme activities.

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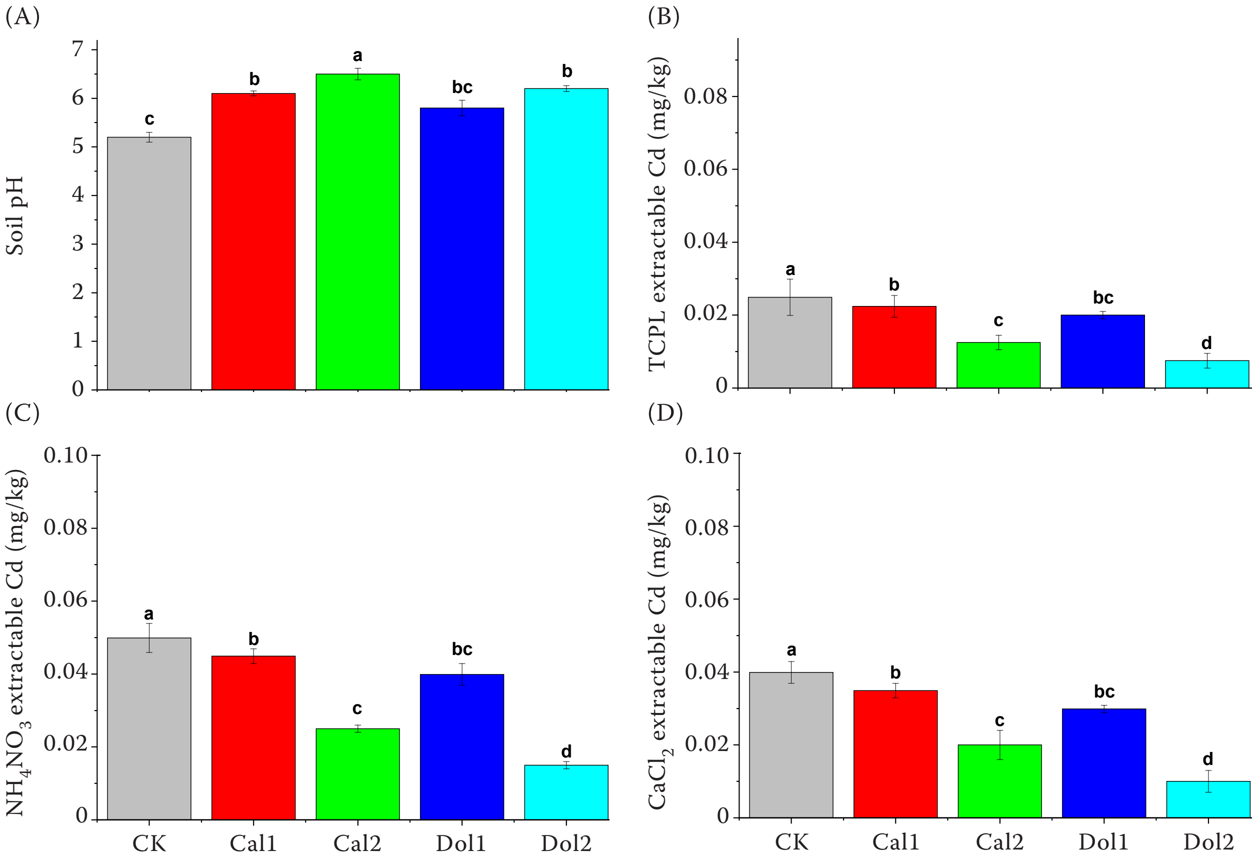

Figure 1. (A) Soil pH and cadmium (Cd) content in soil extracted by (B) toxicity characteristic leaching procedure (TCLP); (C) NH_4NO_3, and (D) $CaCl_2$. Error bars on each column are the standard error of the mean (n = 3). CK – control, no amendments applied; Cal1 – 10 g calcite/kg soil; Cal2 – 20 g calcite/kg soil; Dol1 – 10 g dolomite/kg soil; Dol2 – 20 g dolomite/kg soil. Treatments are significantly ($P \leq 0.05$) different if the letters on each bar are different

The highest recorded enzyme activities in the Dol2 treatment were as follows: urease (6.15 mg NH_4^+-N/g soil/h), catalase (0.74 mL $KMnO_4$/g soil/h), invertase (0.43 mg glucose/g soil/h), phosphatase (5.59 mg phenol/g soil/h), and phenol oxidase (28.37 mmol dicatechol/g soil/h) (Table 1).

Soil organic C and N, and microbial biomasses. Soil DOC and DON contents were lowest in the control

Table 1. Soil health-related enzyme activities at the harvesting time of pak choi

Treatment	Total Cd in soil (mg/kg)	Urease (mg NH_4^+-N/ g soil/h)	Catalase (mL $KMnO_4$/ g soil/h)	Invertase (mg glucose/ g soil/h)	Phosphatase (mg phenol/ g soil/h)	Phenol oxidase (mmol dicq/ g soil/h)
CK	4.80 ± 0.01^a	2.51 ± 0.05^d	0.36 ± 0.01^d	0.25 ± 0.02^d	2.84 ± 0.02^d	12.25 ± 0.52^d
Cal1	4.85 ± 0.01^a	4.65 ± 0.03^c	0.48 ± 0.02^c	0.32 ± 0.01^c	3.81 ± 0.03^c	18.74 ± 0.43^c
Cal2	4.87 ± 0.01^a	5.35 ± 0.04^b	0.65 ± 0.01^b	0.38 ± 0.01^b	4.75 ± 0.02^b	23.56 ± 0.75^b
Dol1	4.89 ± 0.01^a	4.77 ± 0.03^{bc}	0.53 ± 0.01^{bc}	0.35 ± 0.02^{bc}	4.24 ± 0.02^{bc}	22.58 ± 0.61^{bc}
Dol2	4.93 ± 0.01^a	6.15 ± 0.05^a	0.74 ± 0.02^a	0.43 ± 0.02^a	5.59 ± 0.03^a	28.37 ± 0.83^a

CK – control, no amendments applied; Cal1 – 10 g calcite/kg soil; Cal2 – 20 g calcite/kg soil; Dol1 – 10 g dolomite/kg soil; Dol2 – 20 g dolomite/kg soil. Different letters within a column represent significant differences among treatments at $P \leq 0.05$

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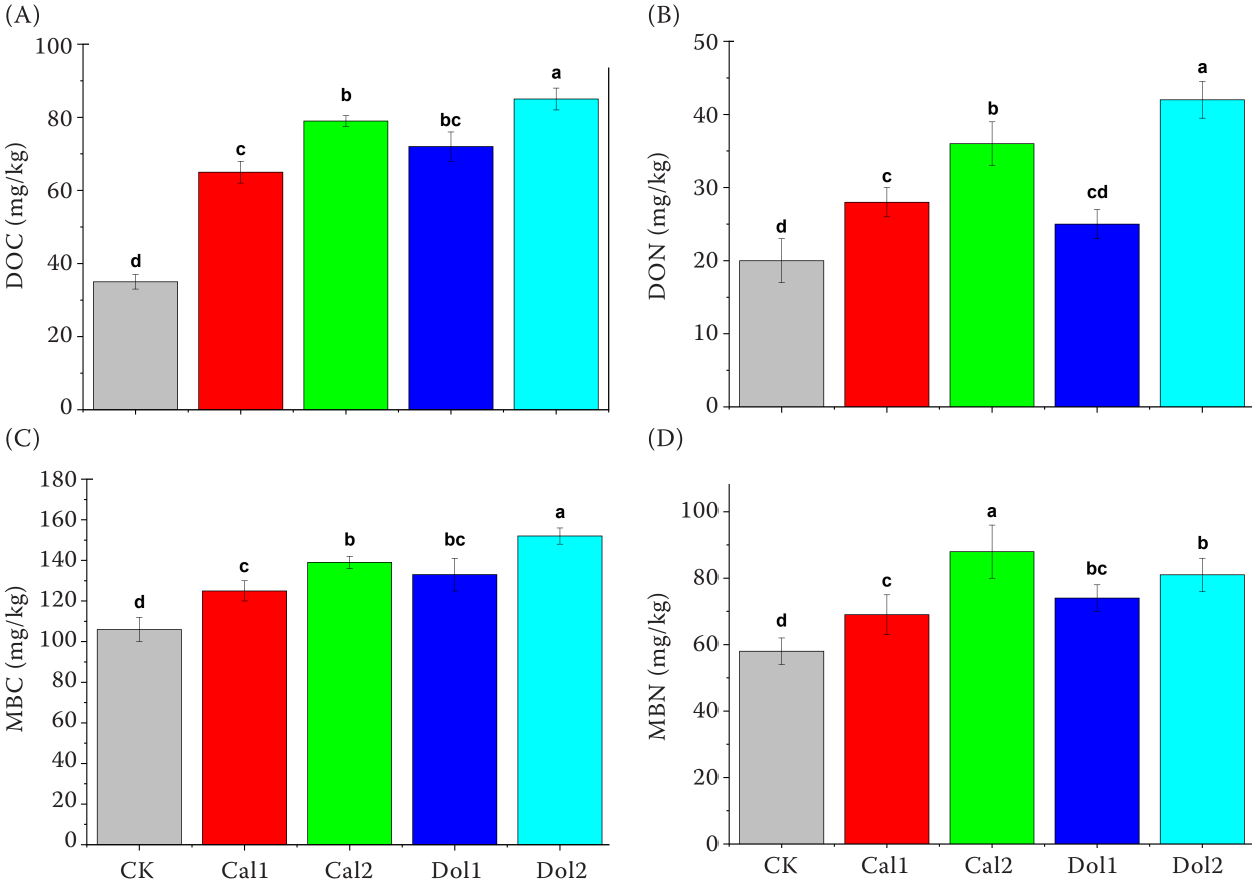

Figure 2. Effect of calcite and dolomite applications on (A) dissolved organic carbon (DOC); (B) dissolved organic nitrogen (DON); (C) microbial biomass carbon (MBC), and (D) microbial biomass nitrogen (MBN). Error bars on each column are the standard error of the mean (n = 3). CK – control, no amendments applied; Cal1 – 10 g calcite/kg soil; Cal2 – 20 g calcite/kg soil; Dol1 – 10 g dolomite/kg soil; Dol2 – 20 g dolomite/kg soil. Treatments are significantly ($P \leq 0.05$) different if the letters on each bar are different

Table 2. Impact of soil amendments on cadmium (Cd) accumulation, chlorophyll, malondialdehyde (MDA), and hydrogen peroxide (H_2O_2) in pak choi

Treatment	Cd in shoot	Cd in root	BAC	BCF	TF	MDA	H_2O_2	Chlorophyll *a*	Chlorophyll *b*	Total chlorophyll
	(mg/kg dry weight)					(μmol/g fresh weight)		(mg/L)		
CK	1.82 ± 0.02^{a}	2.55 ± 0.06^{a}	0.38 ± 0.02^{a}	0.53 ± 0.02^{a}	0.71 ± 0.02^{a}	45.1 ± 0.79^{a}	85.2 ± 1.8^{a}	6.01 ± 0.05^{d}	2.51 ± 0.02^{d}	8.52 ± 0.04^{d}
Cal1	0.91 ± 0.03^{b}	1.91 ± 0.05^{b}	0.19 ± 0.01^{b}	0.39 ± 0.01^{b}	0.48 ± 0.02^{b}	33.5 ± 0.83^{b}	71.3 ± 2.5^{b}	6.58 ± 0.04^{c}	2.94 ± 0.01^{c}	9.52 ± 0.03^{c}
Cal2	0.67 ± 0.05^{c}	1.72 ± 0.04^{c}	0.14 ± 0.01^{d}	0.35 ± 0.01^{d}	0.39 ± 0.01^{bc}	25.3 ± 0.45^{c}	59.5 ± 1.3^{c}	7.24 ± 0.06^{b}	3.35 ± 0.02^{b}	10.59 ± 0.02^{b}
Dol1	0.77 ± 0.04^{bc}	1.79 ± 0.03^{bc}	0.16 ± 0.01^{c}	0.37 ± 0.01^{c}	0.43 ± 0.01^{c}	22.2 ± 0.91^{bc}	65.4 ± 1.7^{bc}	6.98 ± 0.03^{bc}	3.12 ± 0.01^{bc}	10.10 ± 0.03^{bc}
Dol2	0.54 ± 0.02^{d}	1.61 ± 0.04^{d}	0.11 ± 0.01^{e}	0.33 ± 0.01^{e}	0.34 ± 0.01^{d}	16.6 ± 0.24^{c}	48.7 ± 1.1^{c}	7.59 ± 0.02^{a}	3.89 ± 0.02^{a}	11.48 ± 0.02^{a}

BAC – biological accumulation coefficient; BCF – biological coefficient factor; TF – translocation factor; GSH – glutathione; CK – control, no amendments applied; Cal1 – 10 g calcite/kg soil; Cal2 – 20 g calcite/kg soil; Dol1 – 10 g dolomite/kg soil; Dol2 – 20 g dolomite/kg soil. Different letters within a column represent significant differences among treatments at $P \leq 0.05$

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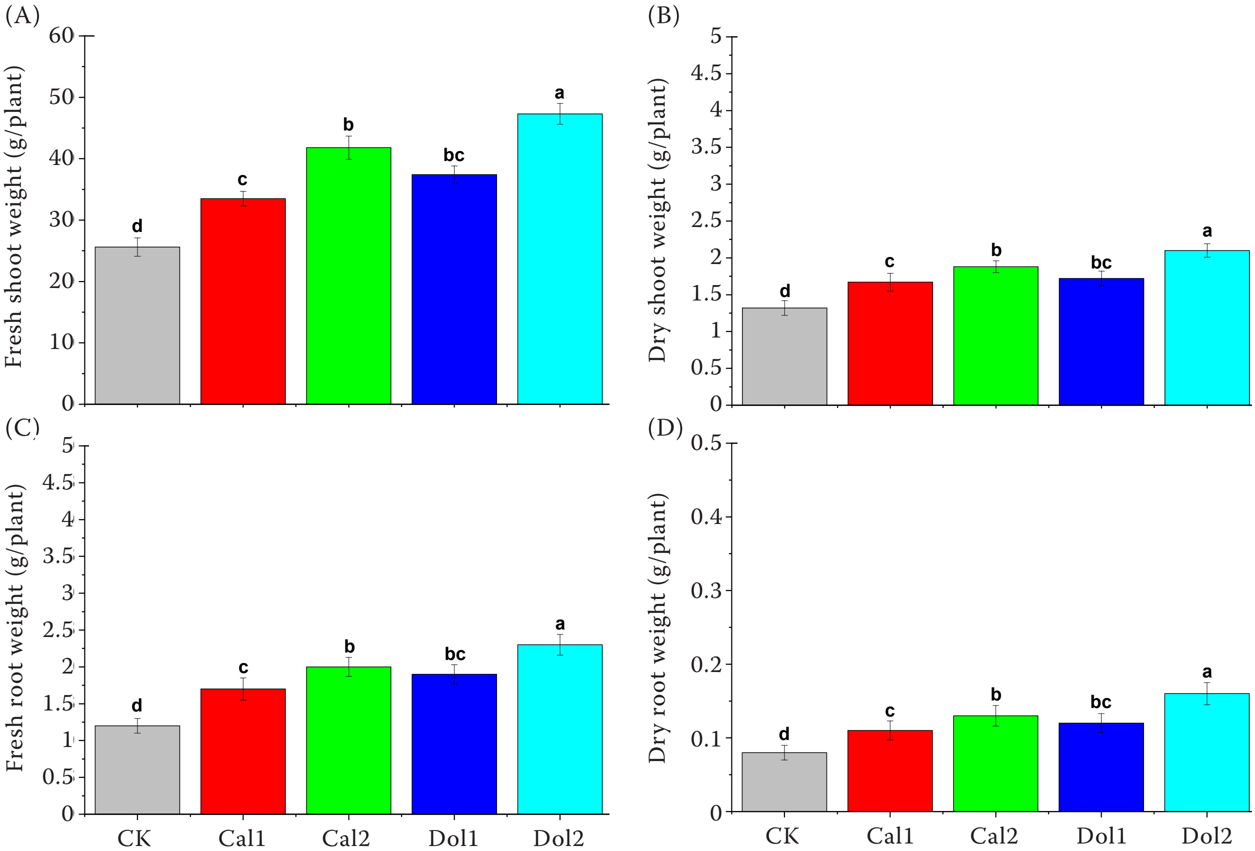

Figure 3. Effect of calcite and dolomite applications on the biomass of pak choi. Error bars on each column are the standard error of the mean (n = 3). CK – control, no amendments applied; Cal1 – 10 g calcite/kg soil; Cal2 – 20 g calcite/kg soil; Dol1 – 10 g dolomite/kg soil; Dol2 – 20 g dolomite/kg soil. Treatments are significantly ($P \leq 0.05$) different if the letters on each bar are different

treatment, while the addition of calcite and dolomite increased their levels, with dolomite having the most pronounced effects. The highest DOC and DON values were 85 and 42 mg/kg, respectively, in the Dol2 treatment (Figures 2A and 2B). Similarly, MBC and MBN were also improved by the application of calcite and dolomite, with maximum values of 152 and 81 mg/kg, respectively, in the Dol2 treatment (Figure 2C, D).

Root and shoot Cd contents and plant growth. Cd concentrations were higher in the roots compared to the shoots, regardless of the treatment. However, both calcite and dolomite significantly ($P \leq 0.05$) decreased Cd levels in both roots and shoots ($P \leq 0.05$), with the lowest levels recorded in the Dol2 treatment: 1.6 mg/kg dry weight in the roots and 0.54 mg/kg dry weight in the shoots (Table 2). Fresh and dry weights of root and shoot biomass were lowest in the control treatment (fresh shoot: 25.6 g/plant, dry shoot: 1.32 g/plant, fresh root: 1.2 g/plant, dry root: 0.08 g/plant). The highest biomass values were observed in the Dol2 treatment compared to the CK (Figure 3A–D). The lowest values of BAC, BCF, and TF were observed in the Dol2 treatment compared to all other treatments, with BAC, BCF, and TF values of 0.11, 0.32, and 0.34, respectively (Table 2). MDA and H_2O_2 concentrations were also significantly reduced with the application of dolomite and calcite, with the lowest levels of 16.6 and 48.7 μmol/g fresh weight, respectively, in Dol2 treatment (Table 2). The application of dolomite and calcite significantly ($P \leq 0.05$) increased the chlorophyll a and b contents in pak choi, with the highest values of 7.59 and 3.89 mg/L, respectively, in Dol2 treatment (Table 2).

Antioxidant enzymes. The highest activities of all tested antioxidant enzymes, including CAT, SOD, POD, and GSH, were observed in the control treatment (Figure 4). However, the application of both dolomite and calcite significantly ($P \leq 0.05$) reduced their activities in pak choi. Dolomite was more effective than calcite, with the Dol2 treatment showing the greatest reduction in enzyme activities. The lowest recorded values in Dol2 were 13 μmol/min/

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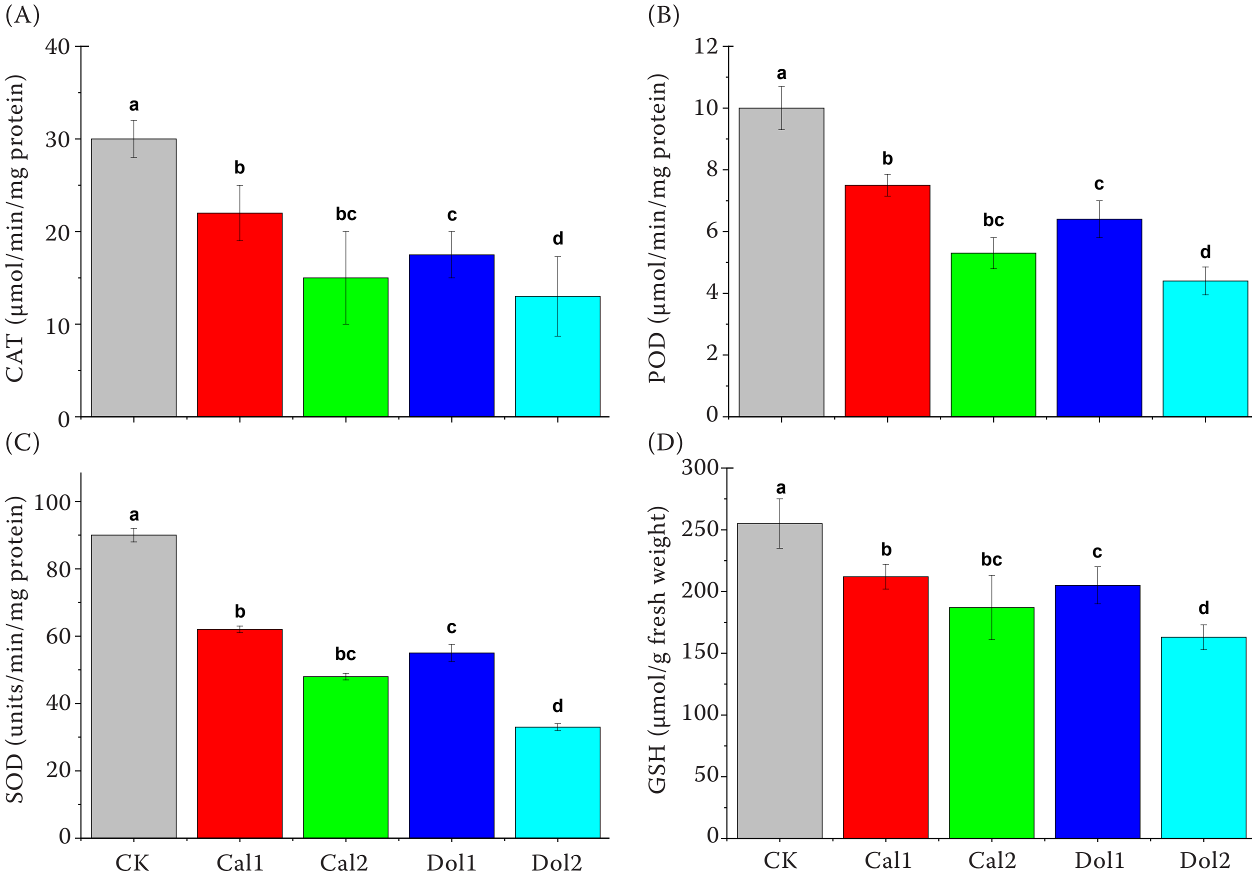

Figure 4. Dynamics of antioxidant enzymes in pak choi. (A) Catalase (CAT); (B) superoxide dismutase (SOD); (C) glutathione (GSH), and (D) peroxidase (POD). Error bars on each column are the standard error of the mean (n = 3). CK – control, no amendments applied; Cal1 – 10 g calcite/kg soil; Cal2 – 20 g calcite/kg soil; Dol1 – 10 g dolomite/kg soil; Dol2 – 20 g dolomite/kg soil. Treatments are significantly ($P \leq 0.05$) different if the letters on each bar are different

mg protein, 4.4 µmol/min/mg protein, 33 units/min/mg protein, and 163 µmol/g fresh weight for CAT, POD, SOD, and GSH, respectively (Figure 4).

Pearson correlations. Pearson correlation analysis (data not shown) revealed strong and significant relationships among soil chemical, biochemical, and biological parameters. Soil pH showed highly positive correlations with urease (r = 0.88, P < 0.01), invertase (r = 0.81, P < 0.01), phosphatase (r = 0.80, P < 0.01), and phenol oxidase (r = 0.77, P < 0.01), indicating that a higher pH environment favoured enhanced enzyme activities. Conversely, Cd fractions extracted by NH_4NO_3 and $CaCl_2$ were negatively correlated with soil pH (r = −0.73 and −0.34, P < 0.01) and all measured enzymes (r = −0.78 to −0.92, P < 0.01), demonstrating that increasing Cd mobility inhibited soil biochemical functioning. Similarly, significant negative correlations were found between Cd concentrations in plant tissues (shoot and root Cd) and soil enzyme activities, MBC and MBN, as well as plant biomass traits (r = −0.88 to −0.99, P < 0.01). In contrast, soil DOC, DON, MBC, and MBN were strongly and positively correlated with each other (r = 0.85 to 0.99, P < 0.01) and with enzyme activities, signifying their mutual contribution to soil fertility and microbial functioning. The negative correlations between MDA, H_2O_2, and enzymatic or biomass parameters further indicate that oxidative stress intensified under higher Cd bioavailability.

DISCUSSION

Liming materials increase soil pH, thereby reducing Cd mobility and enhancing its immobilisation (Papadimou et al. 2024, Zhou et al. 2024). Both calcite and dolomite have been found effective in raising soil pH and immobilising Cd. However, dolomite has shown greater efficacy compared to calcite in stabilising Cd in the soil in the present study. Dolomite is more effective than calcite for

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immobilising Cd in acidic soil due to its unique chemical composition and superior soil-amendment properties (McHale and Winterhalder 1996). Unlike calcite, which consists solely of calcium carbonate ($CaCO_3$), dolomite contains both Ca^{2+} and Mg^{2+} in the form of $CaMg(CO_3)_2$. The differences in affinity between Mg and Ca for Cd substitution are rooted in their distinct ionic and binding properties. Mg^{2+}, with a smaller ionic radius (0.72 Å) compared to Ca^{2+} (1.00 Å), possesses a stronger hydration shell and higher hydration energy, making its substitution by Cd^{2+} less favourable from a purely energetic perspective (Tang et al. 2021). The presence of Mg in dolomite enhances Cd immobilisation by promoting more substantial precipitation and co-precipitation reactions, resulting in the formation of stable Cd-containing minerals such as $CdCO_3$ (otavite) with lower solubility in soil (McHale and Winterhalder 1996). Since Cd is more mobile and bioavailable in acidic conditions, this stronger pH increase reduces its solubility, facilitating precipitation as Cd hydroxides or carbonates (Vrînceanu et al. 2019). The Mg in dolomite can displace weakly bound cations such as H^+ and Na^+ from exchange sites, enhancing Cd adsorption onto soil particles and reducing its leaching potential. These combined factors make dolomite a more effective amendment for reducing Cd availability in acidic soils, ultimately minimising its uptake by plants and lowering environmental risks.

The increased activities of urease, catalase, invertase, phosphatase, and phenol oxidase in Cd-polluted soil following the application of calcite and dolomite suggest an overall improvement in soil biological health and microbial activity, which plays a crucial role in Cd immobilisation (Liu et al. 2022, Li et al. 2023b). The enhancement of these enzyme activities can be attributed to the increased soil pH resulting from the application of liming materials (Shaaban et al. 2023b), which reduces Cd toxicity to soil microorganisms and promotes their metabolic functions. Urease activity is an indicator of nitrogen cycling and microbial function. Its increase suggests improved microbial activity and organic matter decomposition (Shaaban et al. 2023b), which may contribute to Cd immobilisation through the formation of organic complexes (Kamran et al. 2019). The DOC and DON were increased, followed by the application of calcite and dolomite, indicating their positive impact on urease. Catalase, an antioxidant enzyme, reflects microbial stress responses. Its increased activity indicates reduced Cd-induced oxidative stress, allowing microbial communities to thrive and contribute to the stabilisation of Cd through biochemical processes (Kamran et al. 2019). Higher levels of MBC and MBN indicate a thriving soil microbial community, which was enhanced by the application of soil amendments in the present study. Invertase is involved in carbon cycling, and its enhanced activity suggests improved microbial activity and the decomposition of organic matter (Shaaban et al. 2023b). The enhanced microbial processes can indirectly influence Cd dynamics through changes in soil organic matter composition and availability of binding sites. Phosphatase plays a key role in phosphorus mineralisation. Its increase could enhance phosphate availability, leading to the formation of insoluble Cd-phosphate complexes, further reducing Cd mobility (Kamran et al. 2019). Phenol oxidase is involved in the degradation of organic compounds and humification processes (Shaaban et al. 2023b), which may contribute to Cd immobilisation through enhanced organic matter interactions and complexation. The combined effects of increased microbial activity, organic matter interactions, and potential Cd precipitation reactions contribute to reducing Cd mobility. In addition, Cd biotransformation and bioaccumulation within microbial pathways further support the role of dolomite and calcite as effective amendments for decreasing Cd bioavailability in acidic soils.

The biomass of pak choi was markedly reduced by Cd application. Excessive Cd content in soil has been shown to hinder root development, inhibit photosynthesis, and reduce plant biomass (Kamran et al. 2019). However, the biomass of pak choi increased with the addition of calcite and dolomite. This improvement may be attributed to the ability of dolomite to mitigate the toxic effects of Cd on pak choi, increasing biomass (Li et al. 2024). Additionally, the higher soil pH resulting from dolomite application may alleviate acidic stress on the roots, thereby promoting pak choi growth (Li et al. 2024). The BCF, BAC, and TF for Cd were significantly decreased with the addition of dolomite and calcite. BCF and BAC are crucial indicators of Cd accumulation in the shoot and root of pak choi cultivated in Cd-polluted soil, while TF measures the movement of Cd from the root to the shoot (Malik et al. 2010). Thus, the reduction in Cd bioavailability and uptake following dolomite amendment could be a promising strategy for Cd phyto-stabilisation.

https://doi.org/10.17221/390/2025-PSE

In Cd-polluted soil, the dynamics of antioxidant enzymes CAT, SOD, POD, and GSH in plants typically increase due to oxidative stress (Xu et al. 2019) to counteract the damage caused by reactive oxygen species (ROS). However, calcite and dolomite treatments help reduce the bioavailability of Cd in the soil by neutralising the soil acidity, which may decrease the uptake of Cd by the plant roots (McHale and Winterhalder 1996). As a result, the plant experiences less oxidative stress, and therefore, the activities of the antioxidant enzymes may decrease compared to untreated, Cd-polluted soil (Xu et al. 2019). Furthermore, these treatments enhance soil health, which can lead to improved crop growth. An increase in MDA levels serves as a useful indicator of plant toxicity responses. Elevated MDA levels indicate cellular injury caused by ROS under abiotic stresses such as heavy metal toxicity. (Kamran et al. 2019, Xu et al. 2019). SOD plays a key role in preventing the accumulation of toxic ROS. When cells are exposed to environmental pollutants, SOD activity typically increases to neutralise excess superoxide radicals (O_2^-) through disproportionation reactions (Xu et al. 2019), which helps maintain cellular structural stability and enhances plant resilience against pollutants. However, when dolomite and calcite were applied at higher levels, SOD activity in pak choi was lower than in the control group, suggesting a reduction in Cd-induced oxidative stress and toxicity. POD primarily functions in breaking down excessive hydrogen peroxide (H_2O_2) through catalytic reactions, ensuring cellular stability and improving plant tolerance to pollutants (Xu et al. 2019). Following the addition of dolomite and calcite, POD activity in pak choi decreased by 65% compared to the control. Similarly, CAT plays a comparable role to POD in detoxifying H_2O_2, aiding in plant adaptation to environmental stressors (Xu et al. 2019). The decline in CAT and POD levels corresponded with a decrease in H_2O_2 content, indicating that dolomite and calcite effectively mitigated Cd-induced oxidative stress in pak choi, thereby supporting plant growth. The addition of dolomite and calcite significantly increased chlorophyll content in pak choi. Cd toxicity inhibits chlorophyll biosynthesis, which is a major factor contributing to reduced photosynthesis and stunted plant growth (Kamran et al. 2019). Among all treatments, the Dol2 treatment resulted in the highest chlorophyll content, leading to enhanced plant growth. This finding suggests that mitigating Cd toxicity through dolomite and calcite application can improve photosynthetic efficiency and promote overall plant health.

The findings can also be elucidated through correlation analysis. The strong positive correlations between soil pH, enzyme activities, and microbial biomass demonstrate that pH regulation plays a pivotal role in sustaining microbial functionality under Cd stress. The negative association between exchangeable Cd fractions ($NH_4NO_3^-$ and $CaCl_2$-extractable Cd) and biochemical parameters suggests that Cd toxicity suppresses enzymatic catalysis and microbial metabolism, likely due to enzyme denaturation and membrane damage. The observed positive interrelations among DOC, DON, MBC, and MBN highlight the synergistic role of soil organic substrates in promoting microbial resilience and enzymatic recovery following amendment addition. Conversely, the strong negative correlations of MDA and H_2O_2 with enzyme activities and biomass confirm that oxidative stress is a key mechanism driving Cd-induced inhibition. Collectively, these correlations quantitatively validate the qualitative trends discussed earlier, which indicate that calcite and dolomite alleviate Cd bioavailability by increasing soil pH, enhancing microbial and enzymatic activities, and mitigating oxidative stress, thereby improving soil health and plant growth in Cd-contaminated soils.

Acknowledgment. Supported by the Fundamental Research Funds for Henan University of Science and Technology, Project No. 4024-13510002.

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Received: September 8, 2025
Accepted: November 13, 2025
Published online: December 11, 2025